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An investigation of visual, auditory, and bisensory compensatory tracking

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AN INVESTIGATION OF VISUAL, AUDITORY, AND
BISENSORY COMPENSATORY TRACKING

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ABSTRACT

An Investigation of Visual, Auditory, and Bisensory Compensatory Tracking

Previous investigations comparing visual with auditory compensatory tracking behavior have demonstrated the superiority of visual tracking when both the magnitude and the direction of error was continuously available to the subject. When the trackor performs a multi-dimensional task, evidence favoring one or more modalities is very meager. Most investigators agree, however, that a high degree of coherency (predictability) between stimulus sources aids performance in these situations.

The present study re-examined the relative merits of auditory and visual compensatory tracking in one dimension. In addition, all-visual and bisensory (auditory-visual) compensatory tracking was studied in two-dimensions using continuous sine wave inputs which were either 0°, 90°, or 180° in phase.

It was found that RMS scores for one-dimensional visual tracking were significantly lower than those for one-dimensional auditory tracking; although in the latter case the learning curve never reached asymptote. Several analyses were then made on the two-dimensional data. High correlations were discovered between component responses when subjects were tracking two stimuli from the same

modality and when phase relations between stimuli were 0° and 180°. In addition, a significant difference was found between one-dimensional performance and the corresponding component of two-dimensional performance for visual tracking when phase relations were 90°; but there was no significant decrement in performance for 0° and 180° conditions. The same trend was apparent in the auditory data, although it was not significant at the .05 level. Finally, a statistical comparison of performance for the visual component of the visual-visual task with performance in the visual component of the auditory-visual task proved to be non-significant.

These results suggest that just as the degree of coherency is an important parameter in two-dimensional discrete tasks, so too, phase relations between stimulus inputs are linked to two-dinensional performance when these inputs are sine waves. The data also suggest that performance in a unisensory two-dimensional tracking task is equivalent to that of a two-dimensional tracking task having a bisensory distribution.

INTRODUCTION

Although tracking studies have received considerable attention for many years, very few data exist that compare tracking behavior in more than one sense modality. In one series of compensatory tracking studies (Humphrey & Thompson, 1952 a; Humphrey & Thompson, 1952 b) it was discovered that with a small amount of practice, auditory tracking in one dimension can be performed almost as well as visual tracking, when only the direction of error is presented to the tracker. These experiments made use of simple and moderately complex sine wave courses. Still another experiment by these same investigators (Humphrey & Thompson, 1953) was designed to explore joystick tracking behavior in one dimension when magnitude and direction of error was continuously available to the subject. The results indicated that visual tracking performance was vastly superior to auditory tracking for all courses.

A multidimensional tracking task is defined as having two or more stimulus sources and a dimension of the control system for response to each (Adams, 1967). If two stimulus sources are presented (two-dimensional), then it is further possible to present them to the same sense modality, or the two sources could have a bisensory distribution.

One of the distinguishing characteristics of a two-dimensional visual tracking task is the added requirement on the observer to scan between sources. This added response requirement is a function of the variable called load (number of stimulus sources). Jackson(1958) found that with a visual multidimensional compensatory tracking task, tracking error increased linearly with the number of stimulus sources. One might also expect that the wider the spatial separation between the visual sources, the longer the time between successive visual samplings, and the greater the tracking error. Various studies (Fitts & Simon, 1952; King, 1961) have provided empirical data supporting this expectation. Adams and Xhignesse (1960) used a two-dimensional pursuit tracking task with discrete stimuli to study three important variables related to two-dimensional visual tracking: spatial separation, speed of the signal event change, and the degree of coherency (predictability of the stimulus sources). They concluded that when the input signals have sufficient regularities, anticipation serves to overcome some of the negative effects of the spatial separation of the sources.

A major issue for visual-auditory bisensory tracking is whether there is an interaction which prevents the two stimulus event streams from being processed simultaneously. Adams and Chambers (1962) investigated this problem using a bisensory discrete tracking task in which a probabilistic series of simultaneous auditory and visual stimuli were presented, with each stimulus series requiring a response from a separate hand. Interestingly, the results indicated a net superiority of bisensory over unisensory responding when stimulus events were certain. It was hypothesized that anticipation of certain events resulted in an increase in the speed of the visual response time to that of the faster auditory response time.

Adams (1961) in his review of human tracking behavior suggests that a bisensory task will be superior to a two-dimensional visual tracking task because each stimulus stream, with its own sense modality, gives the operator a higher load carrying capability. In addition, while performing an auditory-visual task the observer does not have to time sample the sources as he does in two-dimensional visual tracking.

The present study will examine the relative merits of visual and auditory compensatory tracking in one dimension, and all-visual and bisensory compensatory tracking in two dimensions. The question of whether there is an interaction which hinders performance in a two-dimensional task will be studied for both visual and bisensory modalities using continuous sine wave inputs rather than discrete stimuli. Although such inputs are cyclic and thus perfectly predictable, task difficulty will be varied by changing the phase relation between tasks. Finally, correlations will be computed between the component responses so as to determine whether an increase in the performance of one task leads to a concomittant increase or decrease in the other task.

METHOD

The four main compensatory tracking tasks under investigation were as follows: visual tracking in one dimension (V), auditory tracking in one dimension (A), visual tracking in two dimensions (VV), and auditory - visual tracking (AV). In addition, component tasks of the VV condition and the AV condition had continuous sine wave inputs which were either completely in phase (0°), completely out of phase (180°), or had one stimulus lagging the other (90°).

The design matrix for this study is shown in Table 1. Sixty-four male undergraduate students served as Ss. Eight subjects were randomly assigned to each of the separate A and V conditions, while twenty-four subjects were likewise assigned to each of the VV and AV tasks. Each of these sets of twenty-four subjects were further categorized into three groups of eight subjects each according to the three phase relations between the component stimulus inputs. Information as to whether operators were right or left handed was obtained at the start of the study.

A six cycle per minute sine wave generated by a Pace TR-10 analog computer served as the forcing function under all experimental conditions. Its amplitude varied plus or minus two volts. For the simple one-dimensional visual tracking task, the tracking error was displayed to

Table 1

Design Matrix Showing the Number of Subjects Participating in each Experimental Treatment

		One Dimensional	
		A	V
		8	8

		Two Dimensional	
		AV	VV
Phase Relation	0°	8	8
	90°	8	8
	180°	8	8

the human operator on the screen of a Tektronix Type 502-A dual beam oscilloscope. Since the task was compensatory in nature, the target appeared as a fixed reference line on the scope and the operator attempted to keep a blip in coincidence with the reference line as the system input forced it away from the target. Had the subject done nothing to null the input, it would have traversed vertically plus or minus $\frac{1}{2}$ inch on either side of the reference line.

The voltage available to the subject for performing the error nulling operation ranged from plus four to minus four. This voltage was controlled by the operator with the use of a 1000 ohm linear potentiometer. The actual tracking control device manipulated was $1\frac{1}{2}$ inch diameter knob which could be rotated through 240°. Rockway, Morgan, and Eckstrand (1958) found that a control-display ratio of 1:3 is optimum for two-dimensional tracking. This value yielded a corresponding scale deflection of plus or minus one inch on the oscilloscope.

System error, defined as the position of the blip relative to the fixed target, was the basic criterion of performance in this study. The same error signal going to the oscilloscope was sent to scoring circuits in the computer. The conventional percent time-on-target score was not used because of the difficulties inherent in defining the target size (Bahrick & Noble, 1966). Instead, root mean square (RMS) error was used as the performance indicant. Squaring the error voltage and integrating the output of the squaring circuit on a capacitor yields a score which, when divided by the trial time is proportional to the variance of the error distribution. An RMS value can be obtained by a square-root transformation. However, there is still one problem related to this measure. Not only are RMS scores a function of the time-varying amplitude of the original error signal, but also the relative sizes of the resistor and capacitor elements associated with the integrating amplifier. This means that the same input fed into the scoring circuits of different experimenters is not likely to yield identical scores. It has therefore been suggested (Briggs, 1966) that all such scores be converted from units of volts to units of visual display. In the present study each RMS voltage was multiplied by .039 inches/volt to achieve this transformation.

The auditory compensatory tracking task was similar to the visual in that again both the magnitude and the direction of the error was presented. In this case, however, subjects were required to null a tone of varying pitch presented with a stereo headset. This tone oscillated at six cpm about a reference frequency of 1325 cps. Its range was from 1125 to 1600 cps. The control knob for the A condition was identical to that used for the V condition. It could vary the frequency from 850 to 1750cps.

Handedness was controlled during both A and V treatments by having half of the subjects from each group use their dominant hand while the other half used their non-dominant hand. In all cases, turning the knob clockwise raised the blip or frequency while turning it counterclockwise had the opposite effect. Finally, the visual tracking signal could either appear on the upper or lower beam of the oscilloscope. Half of the V observers performed the task on the upper portion of the scope while the other half used the lower portion.

During the VV condition subjects were asked to simultaneously perform each of two component visual tracking tasks. One hand controlled the top visual display while the second hand independently controlled the bottom display. The distance between the two control knobs was $4\frac{1}{4}$ inches and the spatial separation between the two fixed reference lines on the oscilloscope screen was four cm. Although both visual input signals were six cpm sine waves, the two tasks were either 0°, 90°, or 180° out of phase. Under optimum performance these three conditions corresponded to having operators learn three sets of relations between their motor movements. For 0° optimum performance could be achieved by having the right hand move in perfect synchrony with the left hand; for 90° the best performance would result when one hand lagged behind the movements of the other hand; while for the 180° treatment least error could be incurred if, as the right hand moved in a clockwise fashion, the left hand moved in a counterclockwise manner and visa versa. In this condition, half of the subjects used their dominant hand in conjunction with the top display (D-T) and their non-dominant hand in conjunction with the bottom display (ND-B), while the other half did just the reverse. Measures were taken of the performance in each component VV task.

The bisensory condition required observers to track a visual signal with one hand and an auditory signal with the other. Again six cpm sine waves were generated with the phase relation between the two dimensions either 0°, 90°, or 180°. Half of the subjects used their dominant hand for the auditory component task and half used their non-dominant hand. As before display position was controlled in the visual component by dividing the groups into top or bottom categories.

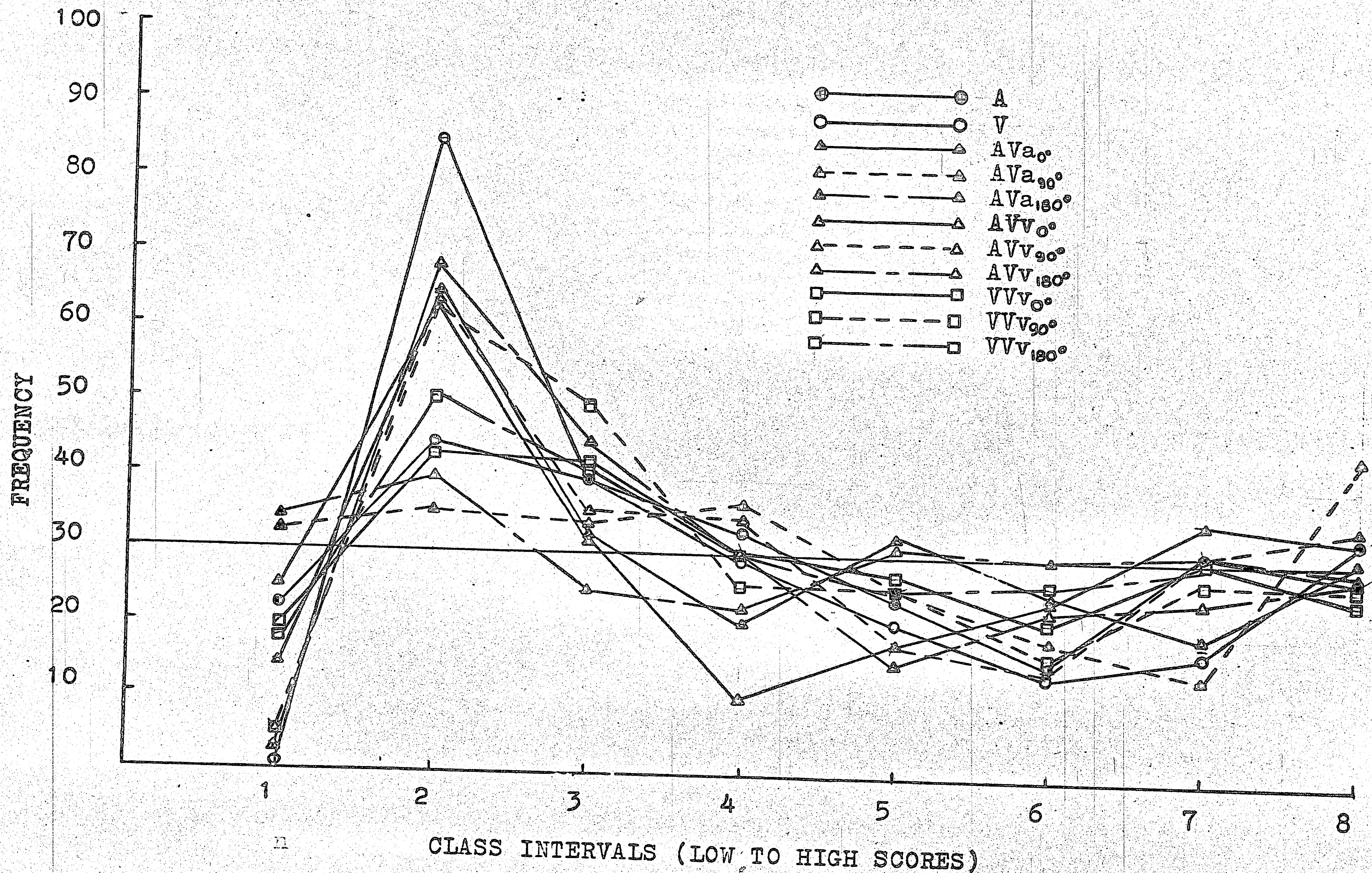
Each subject was given 30-one minute trials with a 30 second inter-trial interval. Although a particular subject was not aware of it, only the final 45 seconds of a given trial were recorded. This gave the trackor a brief period in which to stabilize his response. To facilitate recall during A and AV conditions, subjects were presented the reference pitch for a brief moment before the start of every trial.

RESULTS

Since RMS scores were used as performance indicants, there was some doubt as to whether the distribution of these criterion measures would meet the underlying assumptions in the analysis of variance. Figure 1 shows the frequency with which scores for each of the conditions (auditory and visual components of AV were treated separately) were distributed into 8 class intervals. The intervals were defined in terms of z scores such that if the distributions were in fact normal, then an equal number of scores (30) would be expected to fall in each category. It seems evident that this was not the case and that most distributions were positively skewed. The fact that the distributions were also slightly bimodal discouraged any attempts at transforming the raw data.

The situation is not as hopeless as it may seem. Norton (1952) studied the effects of non-normality on the F-distribution and concluded that the F-distribution is insensitive to the form of the distribution of criterion measures in the parent population, provided that the same form is common to all treatment populations. A further inspection of Figure 1 indicates that treatment populations were quite homogeneous in form. Norton has also suggested that allowance for failure to meet any of the assumptions underlying the F test may be made by setting a higher "apparent" level of significance for the tests of treatment

Figure 1. Frequency polygons for treatment populations. The eight class intervals were defined in terms of z scores such that extremely low scores would fall into interval 1, while extremely high scores would fall into interval 8. Auditory and visual components of AV were treated as separate populations. Treatment populations having approximately 30 scores in each category are considered normal.


FREQUENCY
100
90
80
70
60
50
40
30
20
10
A
V
$AVa_{0°}$
$AVa_{90°}$
$AVa_{180°}$
$AVv_{0°}$
$AVv_{90°}$
$AVv_{180°}$
$VVv_{0°}$
$VVv_{90°}$
$VVv_{180°}$
1
2
3
4
5
6
7
8
CLASS INTERVALS (LOW TO HIGH SCORES)

effects than would otherwise be employed. Therefore, to be on the conservative side, tests quoted at the 5% level were actually tested at the 2.5% level.

A three factor mixed analysis of variance was performed on the V data in order to determine the effects of hand dominance, display position, and performance over trials. The results of this test are provided in Table 2. As can be seen, there was no significant difference between the group which used its dominat hand (D) and the group using its non-dominant hand (ND), and also no difference between the top and bottom display positions. There was however, a significant improvement in performance over trials and a significant interaction effect between handedness and trials. This fact was reflected in F rations of 2.86 and 1.74 for trials and trials by handedness respectively-both significant at the .05 level.

A similar analysis of variance was performed on the A data. In this case, hand dominance was the only main between subject factor, while trials was the within subject factor. Inspection of Table 3 indicates that only trials was significant (F=3.31) at the .05 level.

Figure 2 shows the mean performance for the A group and the mean performance for the V group for 6 blocks of 5 trials. The improvement in performance over trials is quite apparent in both cases-although it is more striking

Table 2

Summary of the Analysis of Variance for One-Dimensional Visual Tracking

Source	SS	d.f.	m.s.	F
Total	306.74	239	---	---
Between Subject	189.13	7	---	---
Dom./Non-Dom.	.68	1	.68	.02
Top/Bottom	25.24	1	25.24	.67
Dom./ Position	12.88	1	12.88	.34
$Error_B$	150.32	4	37.58	---
Within Subject	117.61	232	---	---
Trials	28.97	29	1.00	2.86*
Trials x Dom.	17.56	29	.61	1.74*
Trials x Position	14.46	29	.50	1.43
Trials x Dom. x Position	15.48	29	.53	1.51
$Error_W$	41.14	116	.35	---

* Significant at the .05 level

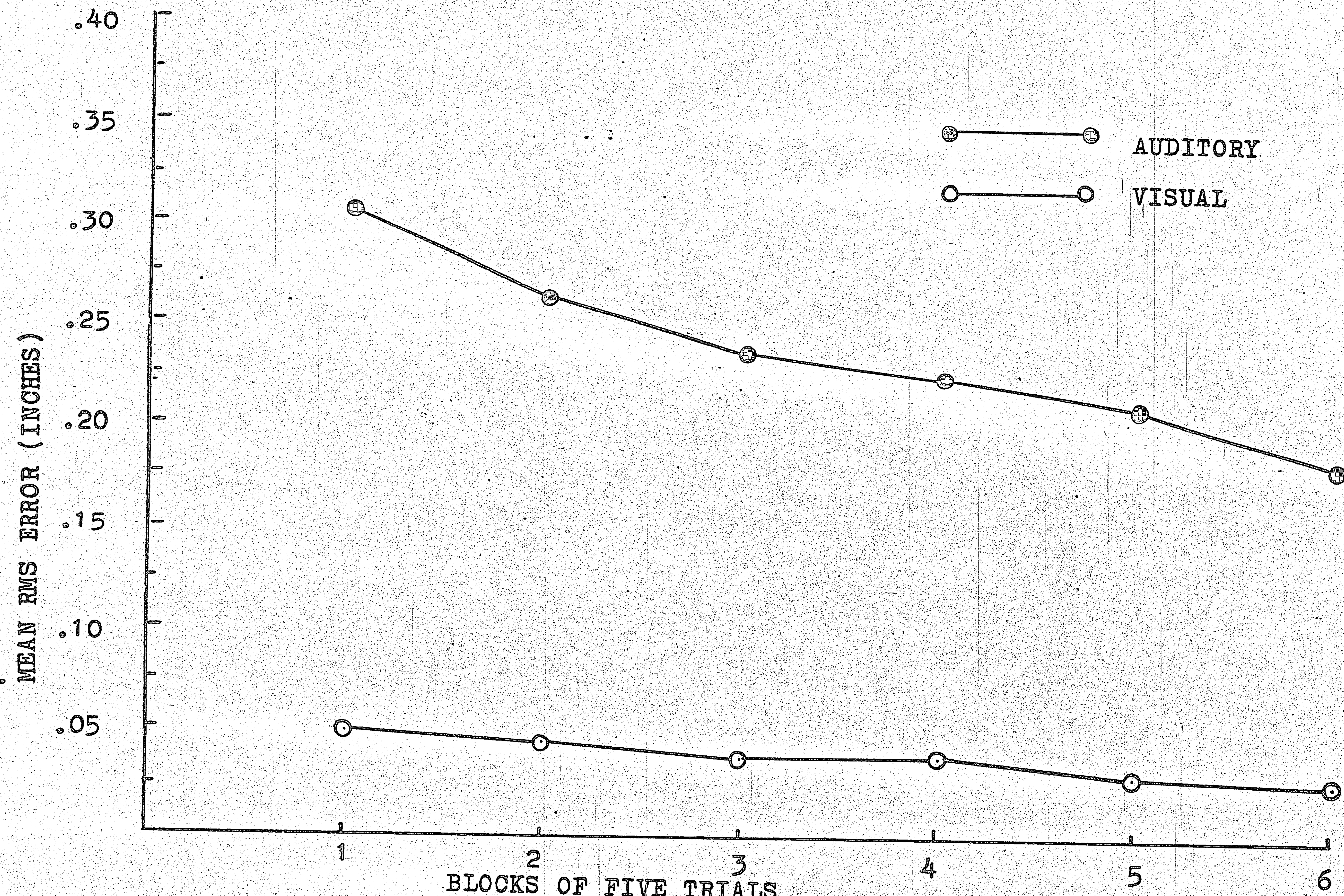
Table 3

Summary of the Analysis of Variance for One-Dimensional Auditory Tracking

Source	SS	df	ms	F
Total	2,747.16	239	---	---
Between Subject	1,627.98	7	---	---
Dom./Non-Dom.	42.78	1	42.78	.16
$Error_B$	1,585.20	6	264.20	---
Within Subject	1,119.18	232	---	---
Trials	357.44	29	12.33	3.31*
Trials x Dom.	112.61	29	3.88	1.04
$Error_W$	649.13	174	3.73	---

* Signigicant at the .05 level

Figure 2. Mean performance for one-dimensional visual tracking and for one-dimensional auditory tracking. Each point represents the mean of eight subjects for five trials.


AUDITORY
VISUAL
MEAN RMS ERROR (INCHES)
.40
.35
.30
.25
.20
.15
.10
.05
1
2
3
4
5
6
BLOCKS OF FIVE TRIALS

for the single auditory task. Another fact to be mentioned is that both curves appear somewhat linear and never appear to reach an asymptote. Finally it seems evident that visual tracking is superior to auditory tracking for the one dimensional case. These expectations were confirmed in a two factor mixed analysis of variance and are presented in Table 4.

The first question which comes to mind in the analysis of both two dimensional tasks (VV and AV) is whether their component tasks should be treated independently or some summary measure should be used (as the total error for the two tasks or the mean error between the two tasks) to describe performance in these conditions. There are two reasons for treating auditory and visual portions of AV separately while considering the two visual components of VV as one score. For one thing, empirically the auditory component of AV (AV_a) yielded scores far different in magnitude than the visual component of AV (AV_v), while there was little difference between component scores in VV. The second reason stems from an analysis of the Peason Product-Moment correlations (r) between component tasks for all subjects performing two tasks simultaneously. Table 5 lists these 48 r values. In general although almost all correlations were positive, correlations between unisensory (VV) component tasks appeared to be much higher

Table 4

Summary of the Analysis of Variance for the Comparison of One-Dimensional Visual Tracking with One-Dimensional Auditory Tracking Over Trials

Source	SS	d.f.	m.s.	F
Total	6,150.05	479	---	---
Between Subject	4,913.26	15	---	---
Auditory/Visual	3,096.15	1	3,096.15	23.86*
$Error_B$	1,817.11	14	129.79	---
Within Subject	1,236.79	464	---	---
Trials	249.83	29	8.61	4.12*
Trials x Aud./Vis	136.58	29	4.71	2.25*
$Error_W$	850.38	406	2.09	---

* Significant at .05 level

Table 5

Pearson Product-Moment Correlations Between Component Tracking Tasks for VV and AV

VV

	0°	90°	180°
Dom. Top/ Non. Dom. Bott.	.81	.74	.78
	.68	.48	.74
	.69	.20	.81
	.73	.45	.81
Dom. Bot./ Non. Dom. Top	.62	.83	.68
	.94	.86.	.67
	.72	.90	.83
	.73	.76	.89

AV

		0°	90°	180°
Dom. Auditory	Top	.49	.00	.76
		.50	.27	.43
	Bott.	.39	.62	.85
		.73	.33	.24
Dom. Visual	Top	.64	.37	.53
		.52	.28	.82
	Bott.	.44	-.01	.79
		.73	.32	.65

than between bisensory component tasks. Statistically this observation can be confirmed only after the correlations of Table 1 have been transformed into Z values using Fisher's Z transformation. Figure 3 presents the mean Z transformations and their corresponding r values for both VV and AV conditions for the three phase relations. A two-way analysis of variance on the data indicated that there was a significant difference (at .05 level) between the VV and AV tasks and also among the phase angles. Table 6 summarizes the F ratios for this test.

In attempting to establish whether AV tracking was superior to VV tracking a comparison was made between AV_v and the mean of the two visual component responses ($VV\bar{V}$). Figure 4 offers the mean tracking data for $VV\bar{V}$ and AVv for the three phase relations between tasks over blocks of five trials. Although it appears from this figure that there might have been some difference between $VV\bar{V}$ and AVv at 90°, a three factor analysis of variance found that the only significant differences were among phase relations and trials with all interactions being non-significant. The summary of this analysis is presented in Table 7.

The auditory portion of the AV task was analyzed separately in order to determine whether performance in this component was affected by the phase angle and if learning took place. Although the results again showed

Figure 3. Mean Z transformations of correlational data for VV and AV tracking at 0°, 90°, and 180°. Each point represents the mean for 8 subjects. Corresponding r values appear adjacent to each point.

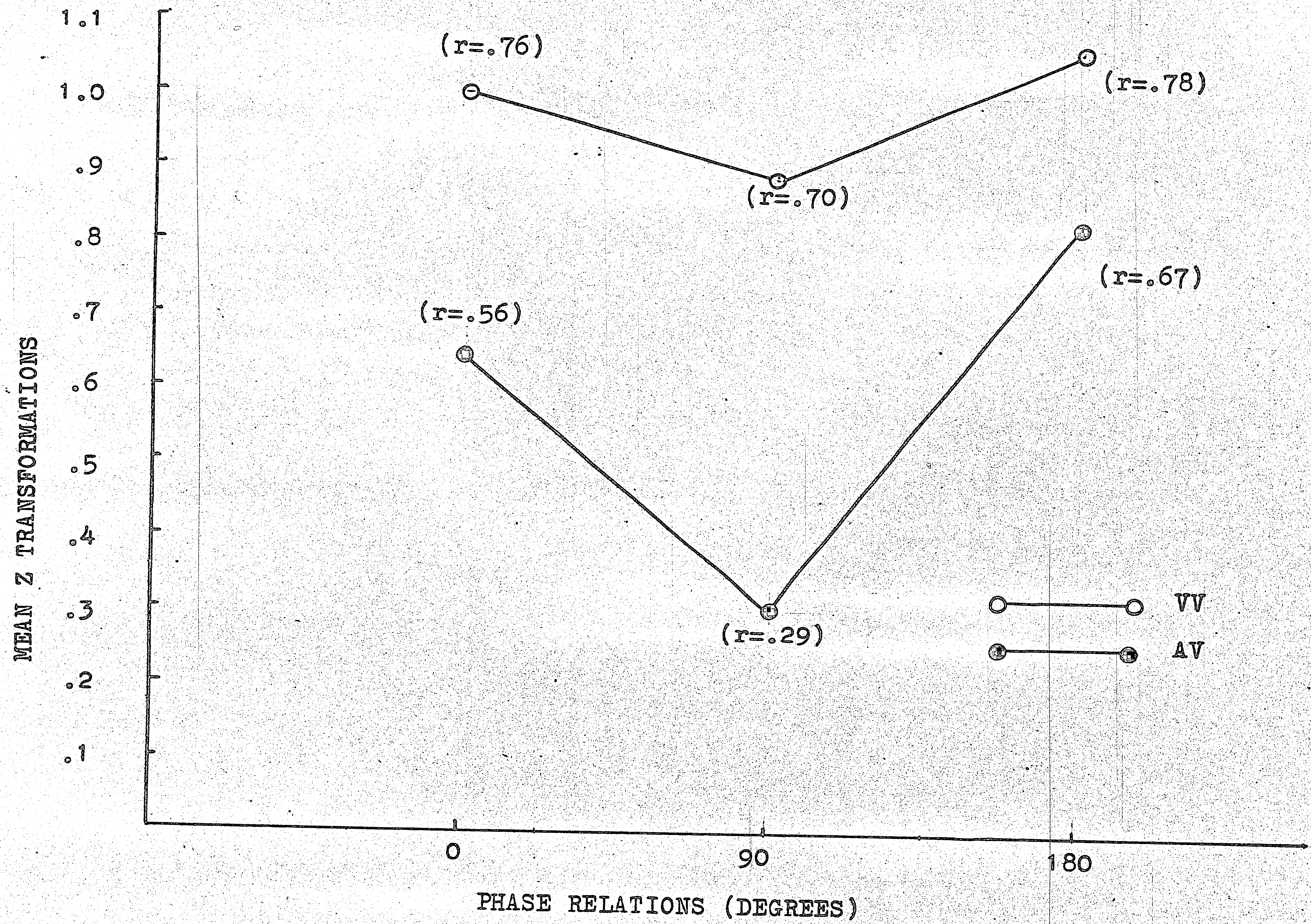

MEAN Z TRANSFORMATIONS
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
(r=.76)
(r=.70)
(r=.78)
(r=.56)
(r=.29)
(r=.67)
VV
AV
0
90
180
PHASE RELATIONS (DEGREES)

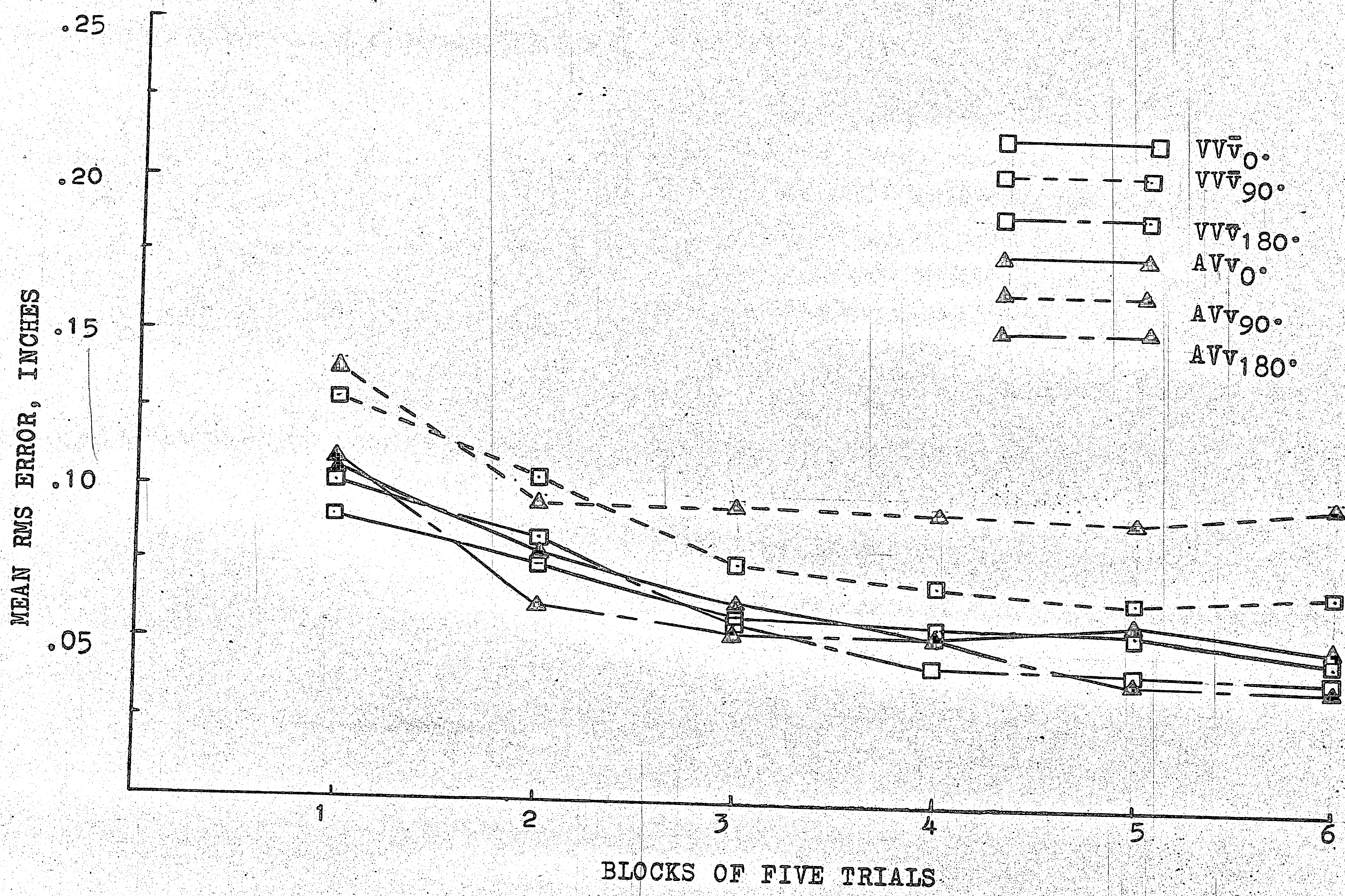
Table 6

Summary of Analysis of Variance Performed on Z Scores

Source	SS	df	ms	F
Total	7.029	47	--	--
VV/AV	1.880	1	1.880	20.22*
Phase	1.008	2	.504	5.42*
VV/AV x Phase	.255	2	.127	1.37
Error	3.886	42	.093	--

* Significant at the .05 level

Figure 4. A comparison of the visual components of bisensory and unisensory two-dimensional tracking for 0°, 90°, and 180° phase relations.



MEAN RMS ERROR, INCHES
.25
.20
.15
.10
.05
1
2
3
4
5
6
BLOCKS OF FIVE TRIALS
$VV\bar{v}_{0°}$
$VV\bar{v}_{90°}$
$VV\bar{v}_{180°}$
$AVv_{0°}$
$AVv_{90°}$
$AVv_{180°}$

Table 7

Summary of the Analysis of Variance for the Visual Components of VV and AV

Source	SS	df	ms	F
Total	2,240.67	1,439	--	--
Between	1,025.09	47	--	--
VV$\bar{v}$/AVv	13.27	1	13.27	.71
Phase	213.92	2	106.96	5.75*
VV$\bar{v}$/AVv x Phase	16.50	2	8.25	.44
$Error_B$	781.40	42	18.60	--
Within	1,215.58	1,392	--	--
Trials	389.62	29	13.44	22.40*
Trials x VV$\bar{v}$/AVv	22.55	29	.78	1.30
Trials x Phase	42.38	58	.71	1.18
Trials x VV$\bar{v}$/AVv x Phase	35.79	58	.62	1.03
$Error_W$	726.24	1,218	.60	--

* Significant at .05 level

a relative superiority of 0° and 180° over 90°, this difference was not significant at the .05 level (the phase relation parameter yielded an F ratio of 2.58). However, as Table 8 reveals, trials remained a highly significant factor.

A final issue which may be raised is how the one-dimensional visual and auditory tracking performance compares with the counterpart component tracking behavior in two dimensions. Duncan's Multiple Range Test was used in making multiple comparisons among the visual tasks and the auditory tasks. In particular, the first analysis compared the following means in order of magnitude: V, $AVv_{180°}$, $VV\bar{v}_{180°}$, $VV\bar{v}_{0°}$, $AVv_{0°}$, $VV\bar{v}_{90°}$, and $AVv_{90°}$. A significant difference was obtained between V and both $VV\bar{v}_{90°}$ and $AVv_{90°}$. Comparing Figure 4 with the visual curve of Figure 2 visually confirms this result.

Figure 5 shows the A learning curve transposed on the curves for $AVa_{0°}$, $AVa_{90°}$, and $AVa_{180°}$. As can be seen, mean A performance was almost identical with that of AVa with 0° and 180° phase relations, while $AVa_{90°}$ tracking was inferior to all others. Duncan's Multiple Range Test, however, failed to show a significant difference between A and AVa for any of the phase angles at the .05 level. Tables 9 and 10 summarize the results of the visual and auditory multiple comparisons.

Table 8

Summary of the Analysis of Variance for the Auditory Component of AV

Source	SS	df	ms	F
Total	11,728.99	719	--	--
Between	7,979.91	23	--	--
Phase	1,552.23	2	790.11	2.58
$Error_B$	6,427.68	21	306.08	--
Within	3,749.08	696	--	--
Trials	1,177.55	29	40.61	10.52*
Trials x Phase	221.13	58	3.81	.99
$Error_W$	2,350.40	609	3.86	--

* Signigicant at the .05 level

Figure 5. A comparison of one-dimensional auditory tracking with the auditory component of AV. Each point represents the mean RMS score for eight subjects during five trials.

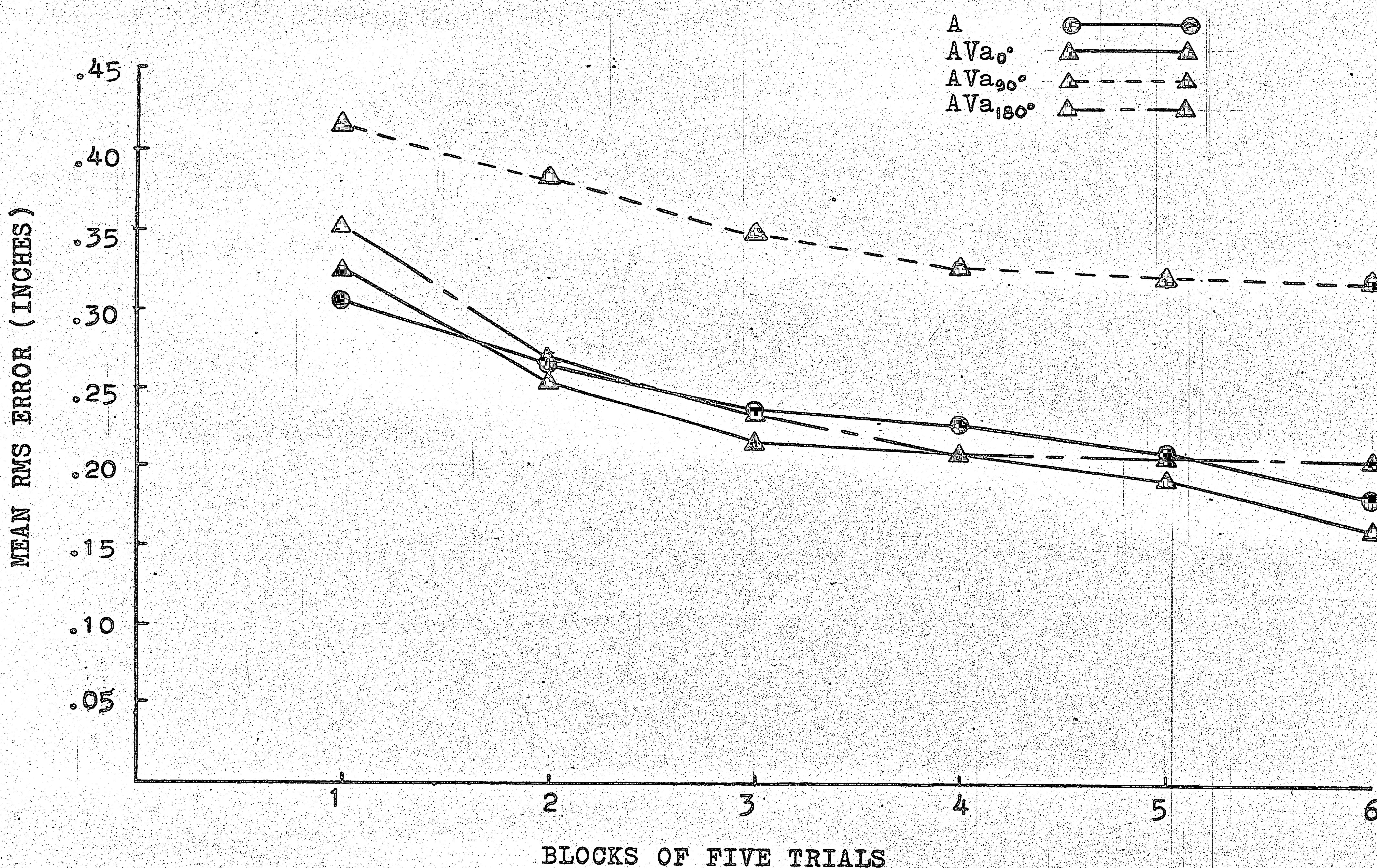

A
AVa0°
AVa90°
AVa180°
MEAN RMS ERROR (INCHES)
.45
.40
.35
.30
.25
.20
.15
.10
.05
1
2
3
4
5
6
BLOCKS OF FIVE TRIALS

Table 9

Duncan's Multiple Range Test for One-Dimensional Visual Tracking and for Visual Components of Two-Dimensional Tracking

	V	$AVv_{180°}$	$VVv_{180°}$	$VVv_{0°}$	$AVv_{0°}$	$VVv_{90°}$	$AVv_{90°}$
V	--	.556	.602	.665	.857	1.234*	1.685*
$AVv_{180°}$		--	.046	.109	.301	.678	1.129*
$VVv_{180°}$			--	.063	.255	.632	1.083*
$VVv_{0°}$				--	.192	.569	1.121*
$AVv_{0°}$					--	.377	.828
$VVv_{90°}$						--	.451
$AVv_{90°}$							--

* Significant at the .05 level

Table 10

Duncan's Multiple Range Test for One-Dimensional Auditory Tracking and for Auditory Components of Two-Dimensional Tracking

	$AVa_{0°}$	A	$AVa_{180°}$	$AVa_{90°}$
$AVa_{0°}$	--	.92	.490	3.330
A		--	.198	3.038
$AVa_{180°}$			--	2.840
$AVa_{90°}$				--

* Significant at .05 level

DISCUSSION

In analyzing the results of the one-dimensional tracking behavior several conclusions can be drawn. The present study appeared to agree with Humphrey and Thompson (1953) in that a visual tracking task in which both the magnitude and direction of error was offered to the observer resulted in far better performance than a comparable auditory tracking task. It must be noted, however, that the slope of the A performance curve shown in Figure 2 is still quite steep at the 30th trial. This fact may indicate that with further practice A performance any equal that of V-or at least more nearly approach it. Regardless of this prediction, one may question why there was such an enormous initial difference in performance between the two tasks. Although every attempt was made to make the two tasks analogous, one basic difference still remained apart from the obvious difference in modality; a fixed reference was present during an entire V trial, which was only present at the start of an A trial. This difference in procedure was initiated in order to avoid masking effects which may have been introduced had both reference and error tone been presented simultaneously. Insofar as memory is more fallible than immediate perception, differences in performance were to be expected between A and V.

Barring any defect in the tracking equipment there should be no reason for any difference in S's performance using the top beam or the bottom beam of the oscilloscope. This expectation was confirmed. It is also not too surprising that on the whole it made little difference which hand was used. There was, however, a significant interaction between handedness and trials during the V condition which resulted from the fact that Ss tracked better with their dominant hand during the early trials.

An interesting discovery made in this study was that there was no significant difference between one dimensional visual tracking performance and the analogous visual component performance of VV and AV for 0° and 180° phase relations. One the surface this evidence would tend to indicate that the human operator has a greater than one channel capacity when performing certain two dimensional tasks. There was, however, an apparent interaction when the two inputs were 90° out of phase resulting in two-dimensional component response measures that failed to achieve the level attained on part tasks. It therefore seems obvious that to be able to predict whether a human will perform as well at two simulanteous tasks requires some knowldege of how these two component tasks are related. This same conclusion was made by others (Adams & Xhignesse, 1960; Fitts & Posner, 1967).

Since all stimulus inputs were continuous sine wave courses, the opportunity for perceptual anticipation was available. However, Poulton (1952) has shown that although anticipatory behavior does occur in compensatory tracking for simple harmonic signals, it is far less than that found in pursuit tracking. With this relative decrease in stimulus anticipation, it might be hypothesized that the operator must compensate by correlating motor responses, not stimuli. In the present study optimal performance would require motor responses which were related to the same extent that stimulus inputs were—either 0°, 90°, or 180° relations between hand movements. If trackers were making use of these response relations as clues to the underlying stimulus inputs, then intuitively it seems that they would be able to learn the 0° and 180° conditions far more readily then the 90° treatment which required a lag between movements.

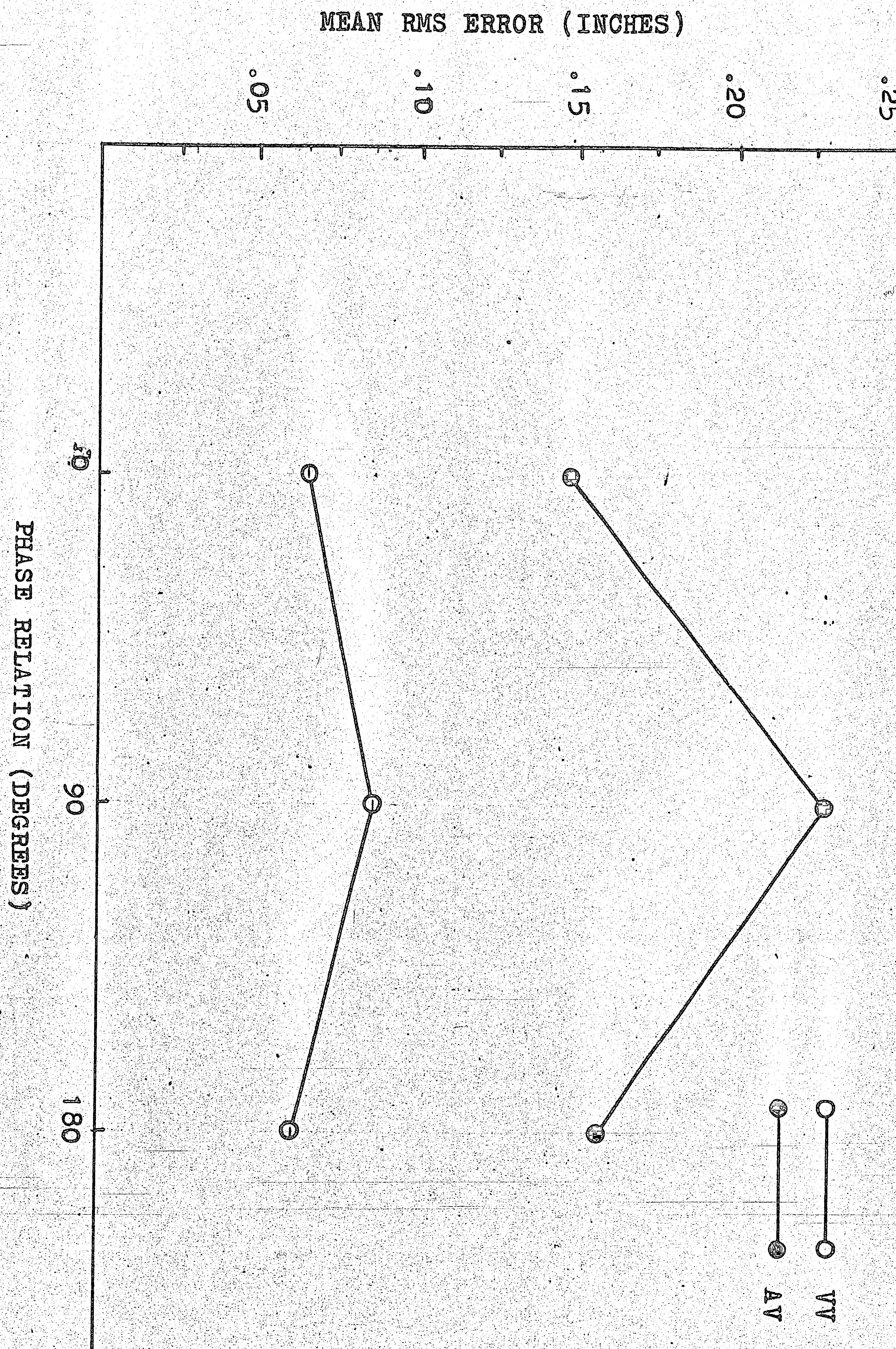
As with V data, a comparison of the one-dimensional auditory task with the auditory component of AV for 0° and 180° phase relations again produced virtually no difference. The main decrement in the auditory component response was realized during AVa_{90}. There are several probable reasons why this difference was not significant at the .05 level. In the analogue recording circuit the maximum squared voltage could not exceed 240 and still be recorded. Four subjects reached this ceiling on an average of 10% of their trials and for this reason the mean auditory error voltage (and consequently inches) might be slightly deflated during the 90° treatment. There was also the greatest subject to subject varialility present for AV tasks.

The hypothesis suggested by Adams (1961) that a two-dimensional bisensory tracking task will be superior to a two-dimensional visual tracking task has to a certain extent been shown to be false. In fact Figure 4 indicates that the visual component of unisensory tracking was slightly superior (although this interaction was not significant at .05 level) to the bisensory component for the 90° condition, with almost no difference for the other phase relations.

The final results to be discussed concern those of the correlation analysis. This approach appears to be unique in the study of multi-dimensional tracking and seems to offer much promise. Intuitively it might be expected that correlations between unisensory tasks would be much higher than those derived from tasks using two different sense modalities. Additionally it might be predicted that r values would be lowest for 90° phase relations, while it is questionable whether there would be any difference in correlations between 0° and 180° treatments. In 90° phase this result might stem from the fact that two sine waves have zero point to point correlations, while those in 0° and 180° phase have perfect correlations. As can be seen from the curves in Figure 3 and the statistical tests in Table 6 these expectations were confirmed.

If the mean of all S's responses are plotted for each of the three phase relations during AV and VV conditions as was done in Figure 6, still another fact emerges. Figure 6 is virtually a mirror image of Figure 3. That is, there is almost a perfect negative relation between the product-moment correlations and the mean tracking errors obtained from two-dimensional data. Thus, in general Ss whose component responses were highly correlated exhibited the smallest magnitude of tracking error; therefore, it is quite possible that correlations may serve as still another indicant of tracking performance for multi-dimensional tasks.

Figure 6. Mean tracking error for unisensory and bisensory two-dimensional tracking with 0°, 90°, and 180° phase relations. Each point represents the mean RMS score for eight subjects over the entire experimental session.


MEAN RMS ERROR (INCHES)
.05
.10
.15
.20
.25
0
90
180
PHASE RELATION (DEGREES)
VV
AV

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VITA

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